



**AFRL-RX-TY-TR-2008-4571**

# **REAR-WHEEL STEERING FOR AIRCRAFT RESCUE AND FIREFIGHTING VEHICLES; TEST AND EVALUATION**

**Keith Bagot**  
Federal Aviation Administration  
William J. Hughes Technical Center  
Airport and Aircraft Safety  
Research and Development Division  
Airport Technology Research and Development Branch  
Atlantic City International Airport, NJ 08405

**Jennifer L. Kalberer, Michael J. McDonald**  
Applied Research Associates  
P.O. Box 40128  
Tyndall Air Force Base, FL 34203

**Virgil J. Carr, Jr.**  
Air Force Research Laboratory

**SEPTEMBER 2008**

**Final Report for 1 December 2006 – 31 March 2007**

**DISTRIBUTION STATEMENT A: Approved for public release; distribution unlimited.**

The use of the name or mark of any specific manufacturer, commercial product, commodity, or service in this publication does not imply endorsement by the Air Force.

**AIRBASE TECHNOLOGIES DIVISION  
MATERIALS AND MANUFACTURING DIRECTORATE  
AIR FORCE RESEARCH LABORATORY  
AIR FORCE MATERIEL COMMAND  
139 BARNES DRIVE, SUITE 2  
TYNDALL AFB FL 32403-5323**

## NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the Air Force Research Laboratory, Materials and Manufacturing Directorate, Airbase Technologies Division, Public Affairs and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (<http://www.dtic.mil>).

REPORT NUMBER AFRL-RX-TY-TR-2008-4571 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

\_\_\_\_\_  
//signature//  
VIRGIL J. CARR, JR.  
Work Unit Manager

\_\_\_\_\_  
//signature//  
SANDRA R. MEEKER  
Chief, Deployed Base Systems Branch

\_\_\_\_\_  
//signature//  
ALBERT N. RHODES, Ph.D.  
Acting Chief, Airbase Technologies Division

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

<b>REPORT DOCUMENTATION PAGE</b>				<i>Form Approved OMB No. 0704-0188</i>	
<small>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</small>					
<b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>					
<b>1. REPORT DATE (DD-MM-YYYY)</b>		<b>2. REPORT TYPE</b>		<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b>				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b>				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b>					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b>					
<b>15. SUBJECT TERMS</b>					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			<b>19b. TELEPHONE NUMBER (Include area code)</b>

# **Test and Evaluation of Rear-Wheel Steering for Aircraft Rescue and Firefighting Vehicles**

September 2008

DOT/FAA/AR-TN08/43

This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.



U.S. Department of Transportation  
**Federal Aviation Administration**

## **NOTICE**

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof. The United States Government does not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the objective of this report. This document does not constitute FAA certification policy. Consult your local FAA airports office as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: [actlibrary.tc.faa.gov](http://actlibrary.tc.faa.gov) in Adobe Acrobat portable document format (PDF).

1. Report No. <b>DOT/FAA/AR-TN08/43</b>		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle <b>TEST AND EVALUATION OF REAR-WHEEL STEERING FOR AIRCRAFT RESCUE AND FIREFIGHTING VEHICLES</b>				5. Report Date <b>September 2008</b>	
				6. Performing Organization Code	
7. Author(s) <b>Keith Bagot, Jennifer Kalberer*, and Michael McDonald*</b>				8. Performing Organization Report No.	
9. Performing Organization Name and Address  Federal Aviation Administration William J. Hughes Technical Center Airport and Aircraft Safety Research and Development Division Airport Technology Research and Development Branch Atlantic City International Airport, NJ 08405  *U.S. Air Force Research Laboratory (AFRL) Fire Research Group 104 Research Road Tyndall AFB Panama City, FL 32403				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address  U.S. Department of Transportation Federal Aviation Administration Air Traffic Organization Operations Planning Office of Aviation Research and Development Washington, DC 20591				13. Type of Report and Period Covered  <b>Technical Note</b>	
				14. Sponsoring Agency Code  <b>AAS-100</b>	
15. Supplementary Notes					
16. Abstract  The Federal Aviation Administration (FAA) has an ongoing research program to evaluate new technologies for increasing postcrash fire survivability on aircraft and to determine methods to increase the performance capabilities of aircraft rescue and firefighting (ARFF) vehicles. A rear-wheel steering (RWS) system was developed to increase the operational performance characteristics of ARFF vehicles in terms of improving vehicle maneuverability, narrowing the turning diameter, and reducing drag on the tires, which should therefore improve tire life.  The objective of this effort was to evaluate the performance of the FAA 6x6 ARFF research vehicle with and without the RWS system. The performance was measured in terms of changes in turning diameter, tire deflection, tread wear, and actual tire life data from U.S. airports operating 6x6 ARFF vehicles.  Turning diameter results showed that RWS improved the turning diameter in both the clockwise and counterclockwise directions. With RWS, the turning diameter decreased 8.8 feet (9%) in the clockwise direction and 11.32 feet (11%) in the counterclockwise direction. Tire deflection analysis did not show any significant differences with or without RWS. Tread wear results showed that the front and rear tires on both sides had significantly less tread wear over an equivalent 40-mile test distance compared to the wear measured without RWS. RWS extended the life of the rear axle tires by 7 to 11 times compared to tire life without RWS. RWS extended the life of the front axle tires by 1.6 to 2.4 times compared to tire life without RWS. Responses to the airport fire department customer survey indicated that vehicles equipped with RWS showed less tire wear, resulting in extended tire life and increased stability/handling of the vehicle.					
17. Key Words  Rear-wheel steering, Tread wear, Tire deflection, Turning diameter			18. Distribution Statement  This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.		
19. Security Classif. (of this report)  Unclassified		20. Security Classif. (of this page)  Unclassified		21. No. of Pages  26	
				22. Price	

## TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	vii
INTRODUCTION	1
Purpose	1
Objectives	1
Background	1
Related Documentation	2
METHODS AND PROCEDURES	3
Test Method	3
Wall-to-Wall Turning Diameter	3
Tire Deflection	3
Tread Wear	4
Customer Survey	6
TEST RESULTS	7
Wall-to-Wall Turning Diameter	7
Tire Deflection	8
Tread Wear	8
Phase 1—Tread Wear Without RWS	8
Phase 2—Tread Wear With RWS	13
Calculated Maximum Tire Life	17
Customer Survey	17
CONCLUSIONS	18

## LIST OF FIGURES

Figure	Page
1      Michelin XZL Tire	2
2      Rear Wheels on FAA 6x6 Research Vehicle Showing Cameras and Measurement Reference Locations	4
3      Different Features of the Michelin XZL Tire	5
4      Paint Markings Used to Identify Tread Measurement Points	6
5      Depth Micrometer Gauge	6
6      The FAA 6x6 Research Vehicle Showing Axle Positions	9
7      Right Front Tire Tread Wear Data Without RWS	9
8      Left Front Tire Tread Wear Data Without RWS	10
9      Right Middle Tire Tread Wear Data Without RWS	10
10     Left Middle Tire Tread Wear Data Without RWS	11
11     Right Rear Tire Tread Wear Data Without RWS	12
12     Left Rear Tire Tread Wear Data Without RWS	12
13     Example of Degree of Tread Wear	13
14     Right Front Tire Tread Wear Data With RWS	14
15     Left Front Tire Tread Wear Data With RWS	14
16     Right Middle Tire Tread Wear Data With RWS	15
17     Left Middle Tire Tread Wear Data With RWS	15
18     Right Rear Tire Tread Wear Data With RWS	16
19     Left Rear Tire Tread Wear Data With RWS	16
20     Calculated Maximum Tire Life Based on Linear Regression Equations	17

## LIST OF TABLES

Table		Page
1	Michelin Truck Tire Specifications	2
2	Wall-to-Wall Turning Diameter With and Without RWS	7

## LIST OF ACRONYMS

AC	Advisory Circular
AFRL	Air Force Research Laboratory
ARFF	Aircraft rescue and firefighting
FAA	Federal Aviation Administration
OTC	Oshkosh Truck Corporation
RWS	Rear-wheel steering
$R^2$	Regression coefficient of determination

## EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) has an ongoing research program to evaluate new technologies for increasing postcrash fire survivability on aircraft and to determine methods to increase the performance capabilities of aircraft rescue and firefighting (ARFF) vehicles. The recently developed rear-wheel steering (RWS) system was developed to increase the performance characteristics of ARFF vehicles and reduce operational costs incurred in excessive tire wear and replacement.

This evaluation effort was undertaken in response to a request from the FAA Office of Airport Safety and Standards. The memorandum requested that the Airport Technology Research and Development Team at the FAA William J. Hughes Technical Center evaluate the performance and benefits of the RWS option offered on the Oshkosh Truck Corporation (OTC) Striker 6x6 and 8x8 ARFF vehicles. The testing of this system took place under an existing Interagency Agreement between the FAA and the United States Air Force at the Air Force Research Laboratory (AFRL) Fire Research Facility at Tyndall Air Force Base, Florida.

The objective of this effort was to evaluate the performance of the FAA's 6x6 ARFF research vehicle with and without an RWS system for turning diameter, tire deflection, tread wear, and actual tire life data from U.S. airports operating 6x6 ARFF vehicles. The turning diameter of the FAA 6x6 ARFF research vehicle was measured for both left and right turns. Testing was conducted according to the FAA Advisory Circular (AC) 150/5220-10C wall-to-wall turning diameter procedures. Tire deflection measurements were recorded in both clockwise and counterclockwise directions using a video camera, following the AC 150/5220-10C dynamic turning control test procedures. Tread wear was produced by driving the vehicle in a figure-eight pattern for 40 miles. Tread depth was measured according to recommendations from the tire manufacturer, Michelin Corporation, using a depth micrometer.

Turning diameter results showed that RWS improved the turning diameter in both clockwise and counterclockwise directions. With RWS, the turning diameter decreased 8.8 feet (9%) in the clockwise direction and 11.32 feet (11%) in the counterclockwise direction. Tire deflection analysis did not show any significant differences with or without RWS. Tread wear results showed that the front and rear tires on both sides had significantly less tread wear compared to the wear measured while the RWS was disengaged. RWS extended the life of the rear axle tires by 7 to 11 times compared to tire life without RWS. RWS extended the life of the front axle tires by 1.6 to 2.4 times compared to tire life without RWS.

In addition to the three test evaluations, the FAA prepared a customer survey that was emailed to airport fire departments that purchased either the OTC Striker 6x6 or the 8x8 ARFF vehicles between 2002 and 2005. The airport fire department customer survey indicated that vehicles equipped with RWS showed less tire wear, resulting in extended tire life, increased stability, and improved vehicle handling.

## INTRODUCTION

### PURPOSE.

This evaluation effort was undertaken in response to a request from the Federal Aviation Administration (FAA) Office of Airport Safety and Standards. The memorandum requested that the Airport Technology Research and Development Team at the FAA William J. Hughes Technical Center evaluate the performance and benefits of the rear-wheel steering (RWS) option offered on the Oshkosh Truck Corporation (OTC) Striker 6x6 and 8x8 aircraft rescue and firefighting (ARFF) vehicles.

### OBJECTIVES.

The objective of this effort was to evaluate the following operational performance characteristics of the RWS system.

- Turning diameter
- Tire deflection
- Tread wear
- Tire life data from U.S. airports operating 6x6 and 8x8 ARFF vehicles

### BACKGROUND.

ARFF vehicle maneuverability and stability continue to be a concern. New designs in ARFF vehicles have enabled manufacturers to provide larger, faster models that offer large agent capacities to airport fire departments. While enhancements to suspension systems have also been developed, vehicle control, tire scrub, and tire wear continue to be an issue at airport fire departments.

In late 2005, the FAA ARFF program received a new Oshkosh Striker 6x6 ARFF research vehicle. The 2500-gallon vehicle is equipped with independent suspension, RWS, and lateral G-force indicator. The RWS system was designed to improve vehicle maneuverability, narrow the turning diameter, and reduce drag on the tires, which should improve tire life. This is accomplished by incorporating a steering linkage to the rear axle, which allows up to 7 degrees of steer. The RWS is an added feature on both the Striker 6x6 ARFF and 8x8 vehicles at a cost of approximately \$7800. OTC has not tested RWS for improved maneuverability or improved tire wear.

The FAA 6x6 research vehicle is equipped with six Michelin XZL on- and off-road commercial truck tires, as specified in table 1 and shown in figure 1. Two dealers quoted \$2500 and \$3500 for each tire, not including installation and service fees, with a delivery time of 1-2 weeks. Some airport fire departments are changing the tires on their Strikers after 5000 miles of use due to excessive wear. Michelin stated that these tires should provide up to 50,000 miles of use, depending on the operational environment of the vehicle.

Table 1. Michelin Truck Tire Specifications

Size	Tread	Load Rating	Loaded Radius (in.)	Overall Diameter (in.)	Overall Width (in.)	Approved Rims	RPM	Tread Depth (32nds)	Maximum Speed (mph)	Maximum Load Per Tire Single		Tire Weight (lb)
										lb	psi	
24R21	XZL	H	24.8	54.6	23.9	18.00	383	31	55	15,700	85	421



Figure 1. Michelin XZL Tire

#### RELATED DOCUMENTATION.

The following documents relate directly to the issues addressed herein and define the test protocol used during this evaluation.

- FAA Advisory Circular (AC) 150/5220-10C, “Guide Specification for Water/Foam Aircraft Rescue and Fire Fighting Vehicles.” This AC contains performance standards, specifications, and recommendations for the design, construction, and testing of a family of ARFF vehicles.
- ASTM F 1016-93 (Reapproved 2001), “Standard Practice for Linear Tire Treadwear Data Analysis.” This standard describes the elementary linear regression analysis of basic treadwear data.
- ASTM F 421-00, “Standard Test Method for Measuring Groove and Void Depth in Passenger Car Tires.” This standard describes procedures for reporting treadwear data.

## METHODS AND PROCEDURES

### TEST METHOD.

To compare the vehicle performance with and without the RWS system, OTC provided a tow control bracket to lock the RWS function on the FAA 6x6 research vehicle. Tests were conducted to evaluate wall-to-wall turning diameter, tire deflection, and tread wear. All tests were conducted both with and without RWS. The FAA 6x6 research vehicle was equipped with video cameras and measuring devices to collect numerical and visual data. The data were then used to confirm the performance of the FAA 6x6 research vehicle with and without RWS.

### WALL-TO-WALL TURNING DIAMETER.

The turning diameter of the FAA 6x6 research vehicle was measured for both left and right turns. Tests were conducted according to the following FAA AC 150/5220-10C wall-to-wall turning diameter procedure.

1. The FAA 6x6 research vehicle was driven slowly in a full cramp circle (left or right) to establish a steady state in the steering linkage.
2. At approximately three equidistant points (identified as A, B, and C) around the circle, the vehicle was stopped using the service brakes.
3. At each stop, a plumb bob was placed against the outermost point of the vehicle and the spot was marked on the ground directly below where the plumb bob came to rest.
4. The straight line distances between each pair of points (AB, BC, and CA) were measured.
5. The wall-to-wall turning diameter (D) was calculated as follows:

$$S = \frac{\sqrt{AB + BC + CA}}{2}$$

$$D = 2R = \frac{AB \times BC \times CA}{2\sqrt{S(S - AB)(S - BC)(S - CA)}}$$

6. Steps 1 through 5 were repeated with the vehicle moving in the opposite direction.

### TIRE DEFLECTION.

The tire deflection test was conducted to determine if the amount of sidewall deflection would provide an indication of the overall side forces incurred by the vehicle while in an aggressive turn. The test was conducted to establish a relationship between the tire deflection values with the RWS operable and the RWS locked, while operating on the same paved surface with the same speed and turning radius, using a visual indication of side forces incurred by the vehicle.

For example, a lower tire deflection value with the RWS would indicate the RWS is reducing the side forces on the vehicle.

Two video cameras were mounted to rigging connected to the vehicle, and a measuring plate was mounted on the rigging opposite the camera (figure 2). The rigging was built to accommodate mounting the camera in such a way as to maximize the tire deflection field of view while also minimizing vibration to the camera while the truck was in motion. Tire deflection measurements were recorded by the video camera without the RWS and with the RWS in both clockwise and counterclockwise directions. The test setup from the FAA AC 150/5220-10C dynamic turning control were followed. The driver accelerated the FAA 6x6 research vehicle around a 100-foot-diameter circle on a concrete, nongrooved runway surface in 5-mph increments up to a maximum of 15 mph.



Figure 2. Rear Wheels on FAA 6x6 Research Vehicle Showing Cameras and Measurement Reference Locations

### TREAD WEAR.

Tread wear tests were conducted by driving the vehicle in a figure-eight pattern on a dry, concrete, nongrooved runway surface for a distance of 40 miles. The tread sections and tire pressure were measured at approximate 20-mile intervals. All six tires were inflated to OTC-recommended pressures. The test was divided into two phases consisting of the same driving conditions but with the RWS system locked during the first phase and the RWS in use in the second. The vehicle was driven in a figure eight composed of two 150-ft-diameter circles (942 ft of travel per figure eight) at a speed of 15 mph for a distance of 40 miles (224 complete circuits). This procedure was used to create an aggressive test method resulting in accelerated wear of the tires. This method reduced the overall number of miles traveled to determine the effectiveness of

the RWS system. Tread depth was measured according to recommendations from the Michelin Company:

“Tread depth measurement can be taken in several spots across the tread and around the circumference. However, to calculate the remaining amount of rubber (knowing the new tire tread depth) for a given number of miles run, the measurement should always be taken at the same spot on the tread and close to the center groove of the tire”.<sup>1</sup>

Six tread sections (figure 3) across the tire were marked (figure 4) and measured using a depth micrometer (figure 5). A 0- to 1-inch Starrett number 440 micrometer was used.<sup>2</sup> A depth micrometer was used rather than a tire depth gauge because the depth micrometer is graduated in increments of 0.001 inch, and the tire depth gauge is calibrated in 1/32 inch. Repeated measurements in the same location demonstrated that readings within  $\pm 0.003$  inch were accomplished. The finer graduations allowed completion of the tread wear experiment in a shorter driving distance. The tread blocks that were identified for measuring scrub were marked with paint in the groove of the tire at the base of the tread so that the markings were not ground off while driving the vehicle. This procedure was repeated three more times, creating four equidistant measurement locations around the circumference for each tire.

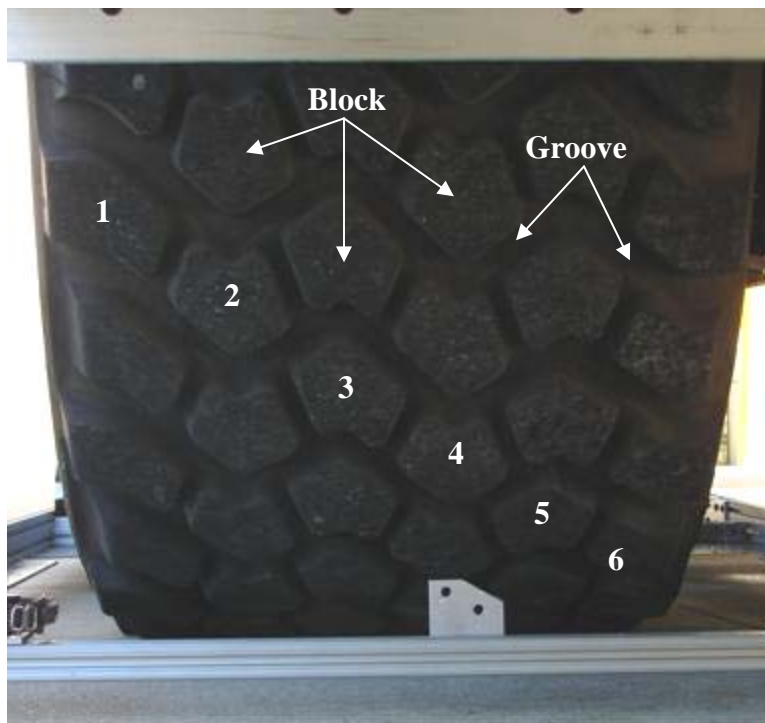


Figure 3. Different Features of the Michelin XZL Tire

<sup>1</sup> Michelin. “Michelin Truck Tire Service Manual,” <http://www.michelintruck.com/michelintruck/toolbox/reference-material.jsp>. September 1996.

<sup>2</sup> AFRL PMEL Identification Number F379885 SESC9, Calibration due 5 October 2008.



Figure 4. Paint Markings Used to Identify Tread Measurement Points



Figure 5. Depth Micrometer Gauge

#### CUSTOMER SURVEY.

The FAA prepared a survey consisting of 9 questions that was emailed to 23 airport fire departments that purchased OTC Striker 6x6 or 8x8 ARFF vehicles between 2002 and 2005. According to OTC records, approximately 2/3 of the vehicles were purchased with the RWS option. Information was requested from airport fire departments that had at least 12 months of

service time to qualify RWS performance and tire wear based on the number of miles driven. The questions submitted to each airport fire department included:

1. When was your 6x6 or 8x8 Striker(s) put into service?
2. How many miles have been driven with the 6x6 or 8x8 Striker(s)?
3. Is your 6x6 or 8x8 Striker(s) equipped with RWS?
4. Have the tires been maintained according to the manufacturers' recommendations?
5. On average, how many miles have you driven on your 6x6 or 8x8 Striker(s) between tire changes?
6. On average, how many miles have you driven on your other 6x6 or 8x8 ARFF vehicle(s) without RWS between tire changes?
7. Have you noticed any difference in tire wear patterns with RWS compared to other vehicles in your fleet that do not have this feature?
8. On average, how long does it take your department to get replacement tires?
9. If applicable, do you feel that RWS enhances the handling or stability of the Striker?

## TEST RESULTS

### WALL-TO-WALL TURNING DIAMETER.

Wall-to-wall turning diameter tests were completed after the tread wear without RWS tests were concluded and after new Michelin XZL tires were installed on axles 1 and 3. The tires on the front and rear axles had a tread depth greater than 0.920 inch at the start of the test, while the tires on the middle axles had a tread depth greater than 0.810 inch at the start of the test. Results showed that RWS improved the turning diameter in both the clockwise and counterclockwise directions. With RWS, the turning diameter decreased 8.8 feet (9%) in the clockwise direction and 11.32 feet (11%) in the counterclockwise direction, as shown in table 2.

Table 2. Wall-to-Wall Turning Diameter With and Without RWS

	Without RWS (feet)	With RWS (feet)	Differences (feet)
Clockwise	97.97	89.17	8.8
Counterclockwise	103.58	92.26	11.32

## TIRE DEFLECTION.

Analysis of the video recorded during the tests did not show any significant differences in tire deflection with or without RWS. The maximum tire deflection measured for each condition was 2 inches. After the video analysis, the Air Force Research Laboratory (AFRL) and the FAA could not make any direct correlations between the amount of sidewall deflection and the overall side forces incurred by the vehicle while in an aggressive turn. AFRL and the FAA determined that this test method did not accurately depict side load forces on the vehicle.

## TREAD WEAR.

Tread wear tests on the FAA 6x6 research vehicle were completed in two phases: Phase 1 was completed without RWS, and Phase 2 was completed with RWS. According to ASTM F 1016-93 Standard Practice for Linear Tire Treadwear Data Analysis, linear tread wear is defined as a constant rate of wear that results in a linear regression coefficient of determination ( $R^2$ ) equal to or greater than 0.95 when obtained from a data set with at least three measurements. According to the standard, the depth loss at the fastest-wearing location may be used if the tire does not show uniform wear between grooves, and the fastest-wearing groove should be used to project tread life. During the tread wear tests, block 1 (outermost block) most often showed the greatest degree of wear and therefore was used for determining  $R^2$  values and calculating maximum tire life.

PHASE 1—TREAD WEAR WITHOUT RWS. At the beginning of Phase 1, all six tires had a tread depth between 0.831 (27/32) to 0.905 (29/32) inch. According to the specifications listed by Michelin, the XZL tire has a manufactured tread depth of 0.969 (31/32) inch. Prior to Phase 1 testing, the FAA 6x6 research vehicle was driven 709 miles while completing predelivery inspection testing before and after installation of the high-reach extendable turret, causing an initial tread wear ranging between 0.064 (2/32) and 0.138 (4/32) inch. Michelin truck tires contain wear bars in the grooves of the tire tread that show up when 0.0625 (2/32) inch or less of tread is remaining. At this stage, the tires must be replaced, according to Title 49 Code of Federal Regulations 393.75, Parts and Accessories Necessary for Safe Operation - Tires. Federal law also requires truck tires on front axles to have at least 0.125 (4/32) inch tread depth.

Three distinct wear patterns based on axle location (figure 6), front, middle, or rear, were observed on the FAA 6x6 research vehicle when the RWS was locked. The tires on the front axle showed equal tread wear during the first 20 miles of driving the figure-eight test pattern (figures 7 and 8). During the second 20 miles, the right front tire continued to wear while the left front tire showed almost no tread wear. Block 1 (outermost block) on the right front showed the most tread wear, decreasing from 0.856 (27/32) to 0.677 (22/32) inch while block 6 showed the least degree of tread wear, decreasing from 0.907 (29/32) to 0.844 (27/32) inch. The  $R^2$  value for block 1 on the right and left front tires were 0.9999 and 0.8386, respectively, indicating linear tire wear on the right side but not the left.



Figure 6. The FAA 6x6 Research Vehicle Showing Axle Positions

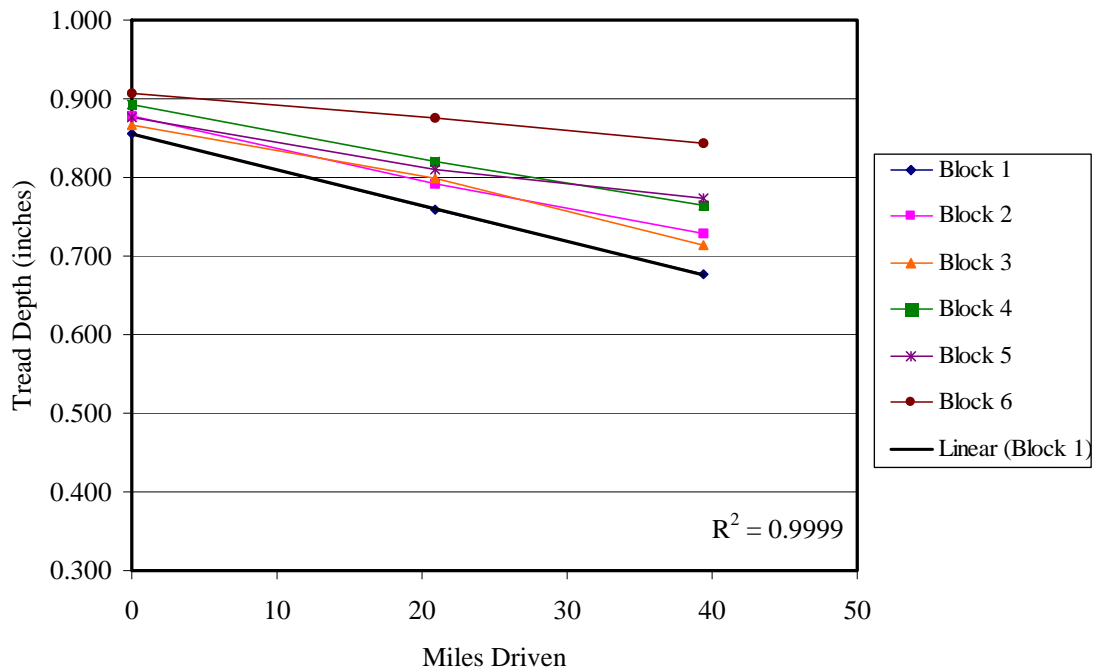


Figure 7. Right Front Tire Tread Wear Data Without RWS

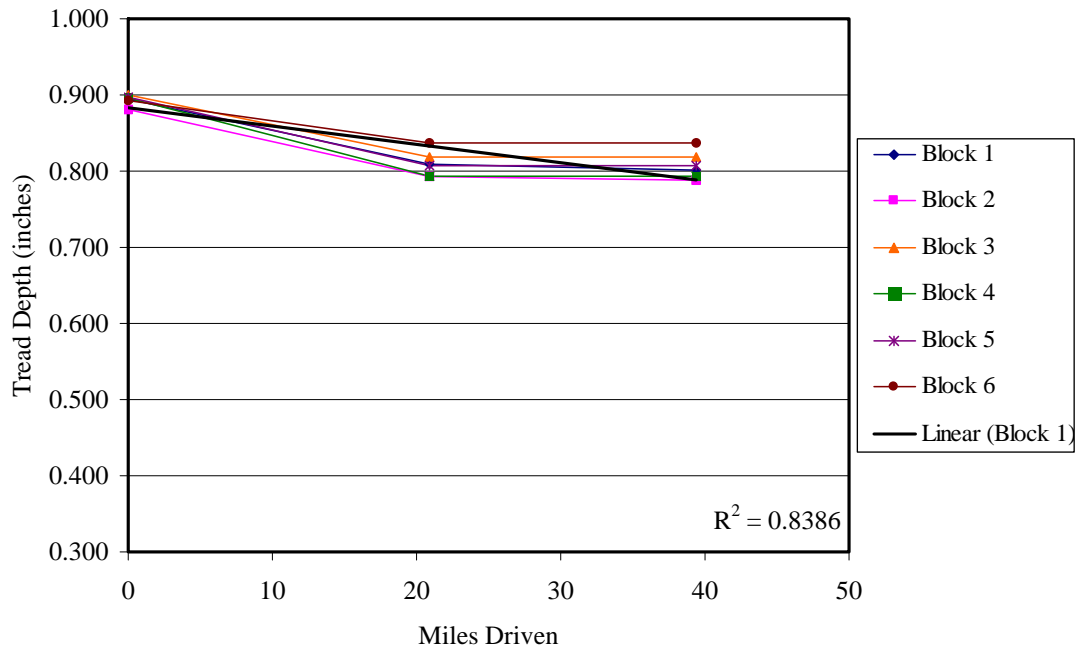


Figure 8. Left Front Tire Tread Wear Data Without RWS

The right and left middle tires showed almost no tread wear throughout the 40-mile evaluation (figures 9 and 10). Block 1 on the right changed from 0.903 (29/32) to 0.894 (29/32) inch while the left middle tire changed from 0.894 (29/32) to 0.880 (28/32) inch. Both tires had  $R^2$  values greater than 0.95, indicating linear tread wear.

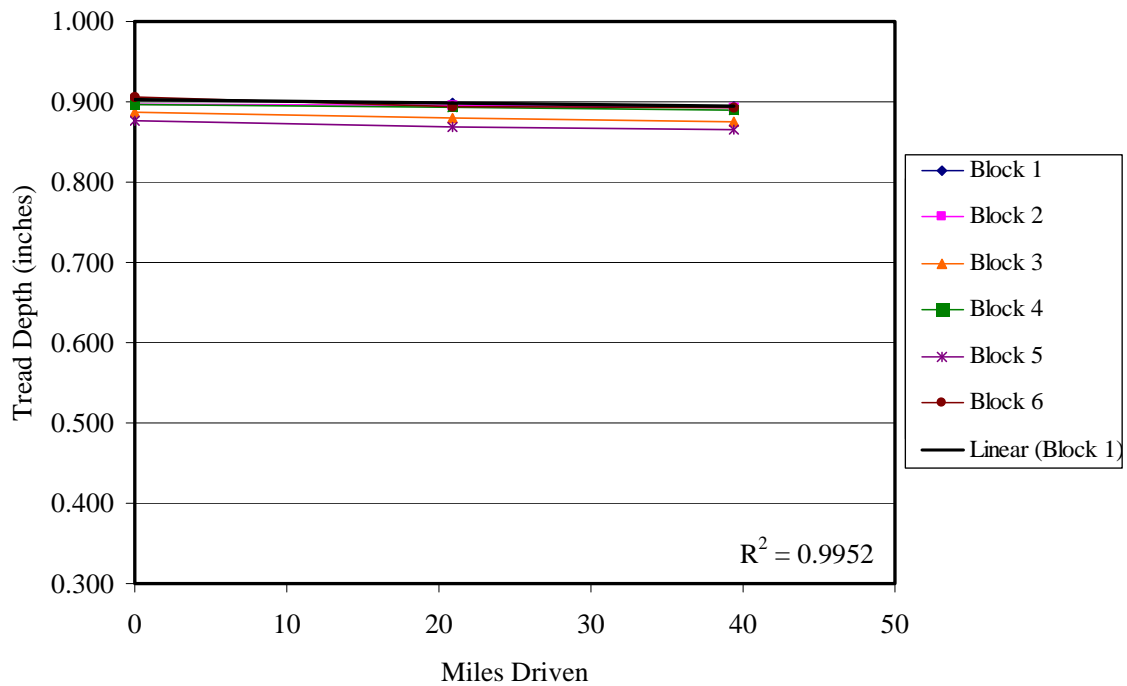


Figure 9. Right Middle Tire Tread Wear Data Without RWS

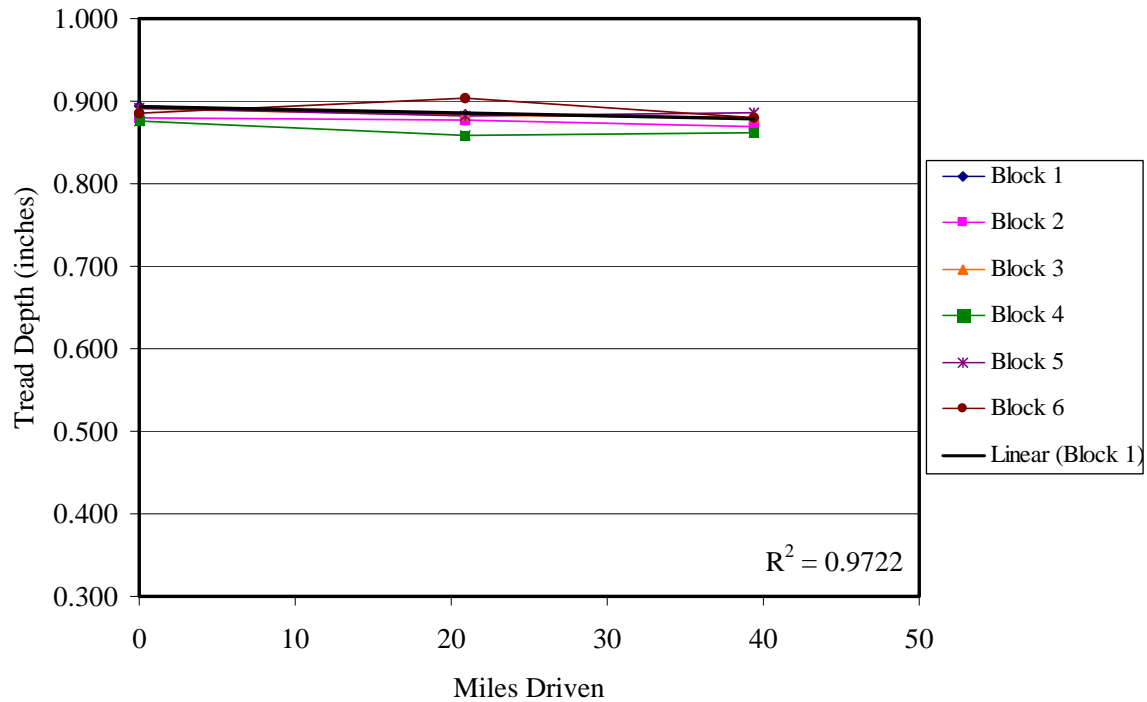


Figure 10. Left Middle Tire Tread Wear Data Without RWS

The greatest degree of tread wear was observed on the two rear tires (figures 11 and 12). Block 1 of the right rear tire decreased from a starting point of 0.880 (28/32) to 0.321 (10/32) inch. The  $R^2$  value was 0.9995, indicating linear tread wear. Block 1 of the left rear tire decreased from 0.884 (28/32) to 0.655 (21/32) inch. Block 1 showed the greatest amount of wear on all the tires except for the rear left, which showed the most tread wear on block 3 (0.862 (28/32) to 0.527 (17/32) inch). Block 1 and 3 on the left rear had  $R^2$  values greater than 0.99, indicating linear tread wear. Figure 13 shows the actual degree of tread wear using a quarter for scale representation of the wear pattern.

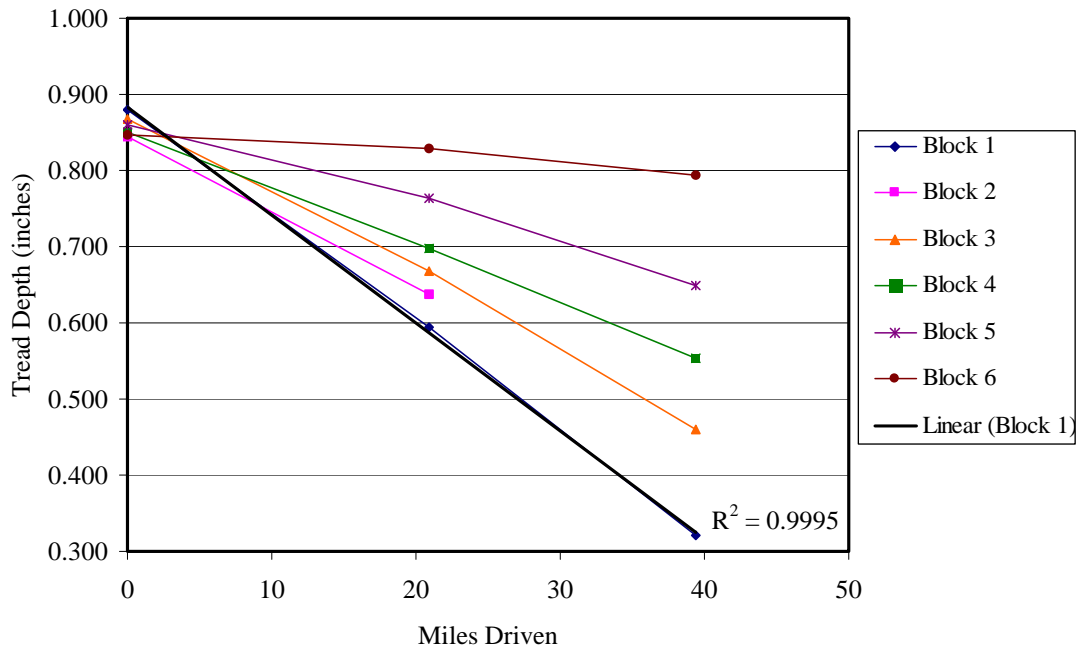


Figure 11. Right Rear Tire Tread Wear Data Without RWS

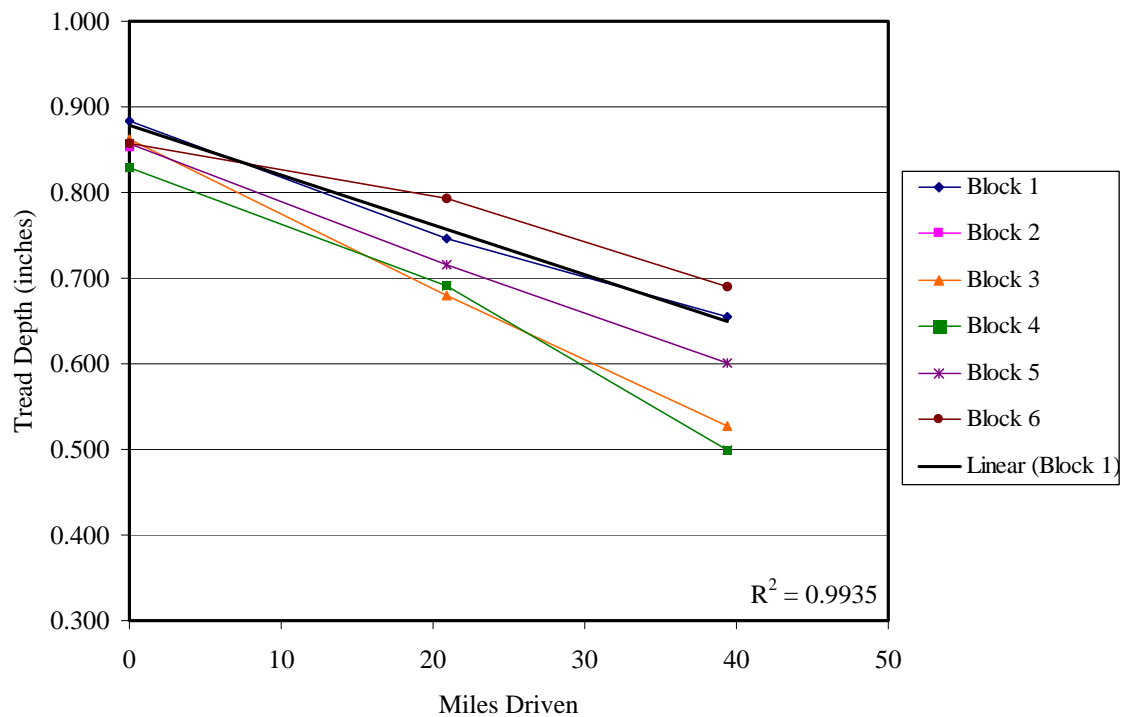


Figure 12. Left Rear Tire Tread Wear Data Without RWS



Figure 13. Example of Degree of Tread Wear

PHASE 2—TREAD WEAR WITH RWS. Four new Michelin XZL tires were installed on the front and rear axles of the FAA 6x6 research vehicle prior to the start of tread wear testing with RWS. All four tires had a minimum initial tread depth of 0.92 (30/32) inch or greater. Linear regression showed an  $R^2$  value greater than 0.95 for all six tires (figures 14-19), indicating linear tire wear. Similar tread wear patterns were observed with RWS as was observed without RWS. The left front and rear tires wore at a slower rate than the right front and rear, while the right middle wore slower than the left middle. The front and rear tires on both sides showed significantly less tread wear over an equivalent 40-mile distance compared to the wear measured with RWS locked. In general, block 1 showed the highest degree of wear compared to the other tread blocks.

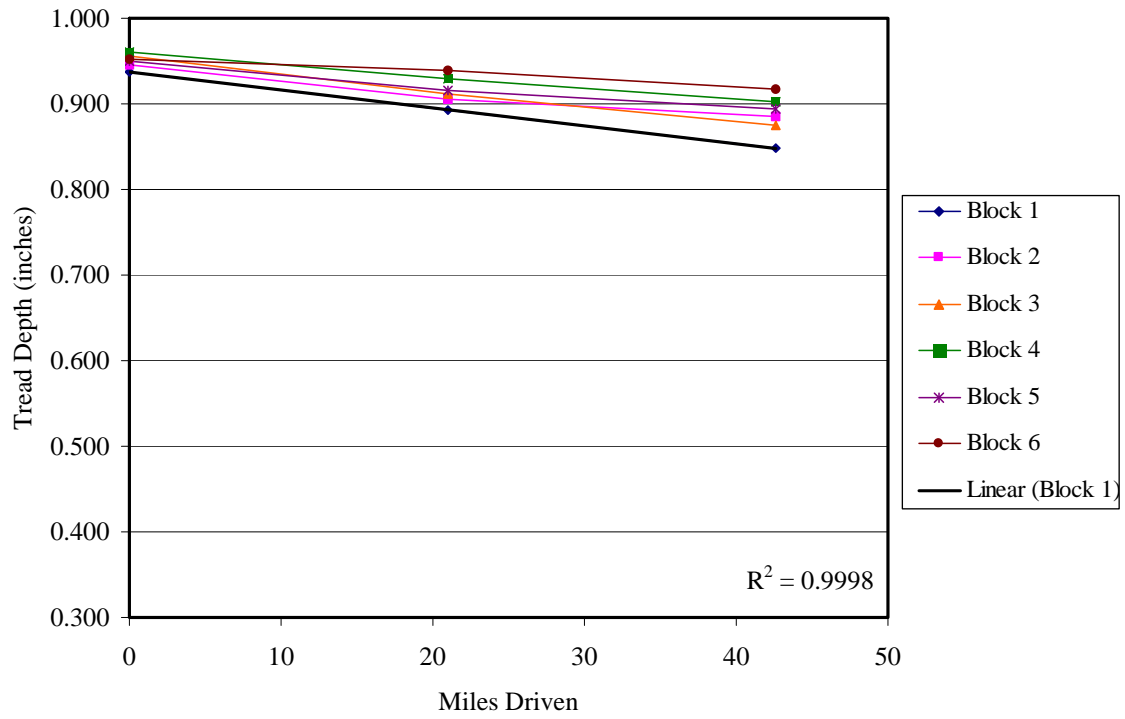


Figure 14. Right Front Tire Tread Wear Data With RWS

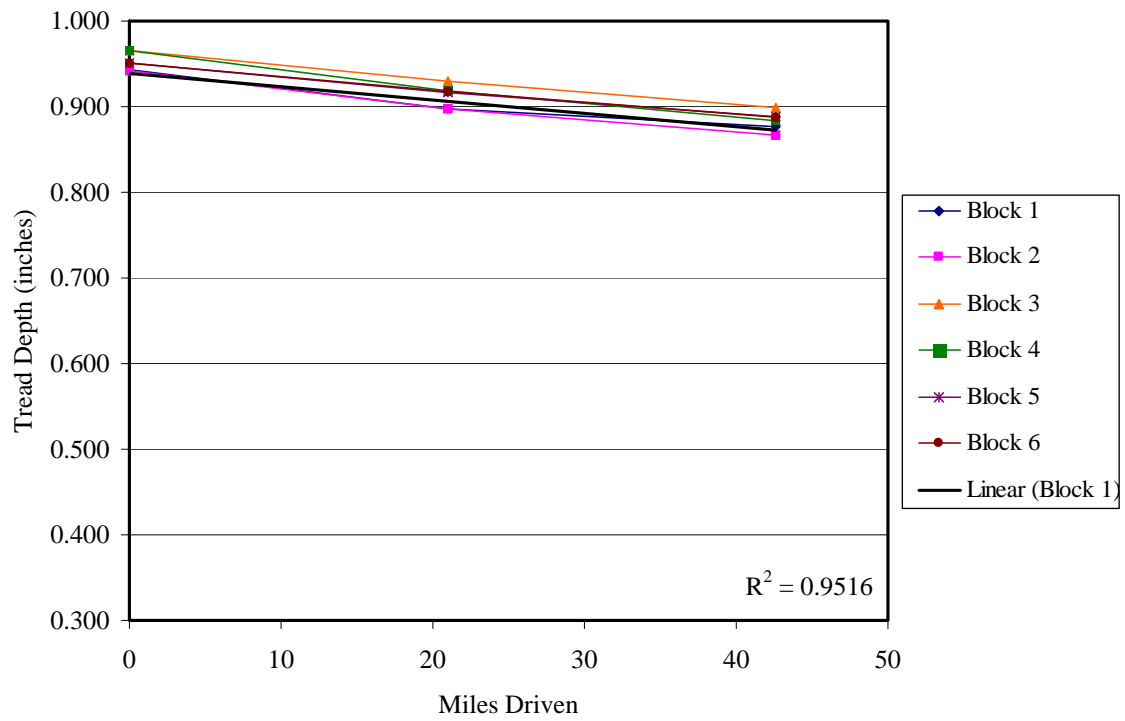


Figure 15. Left Front Tire Tread Wear Data With RWS

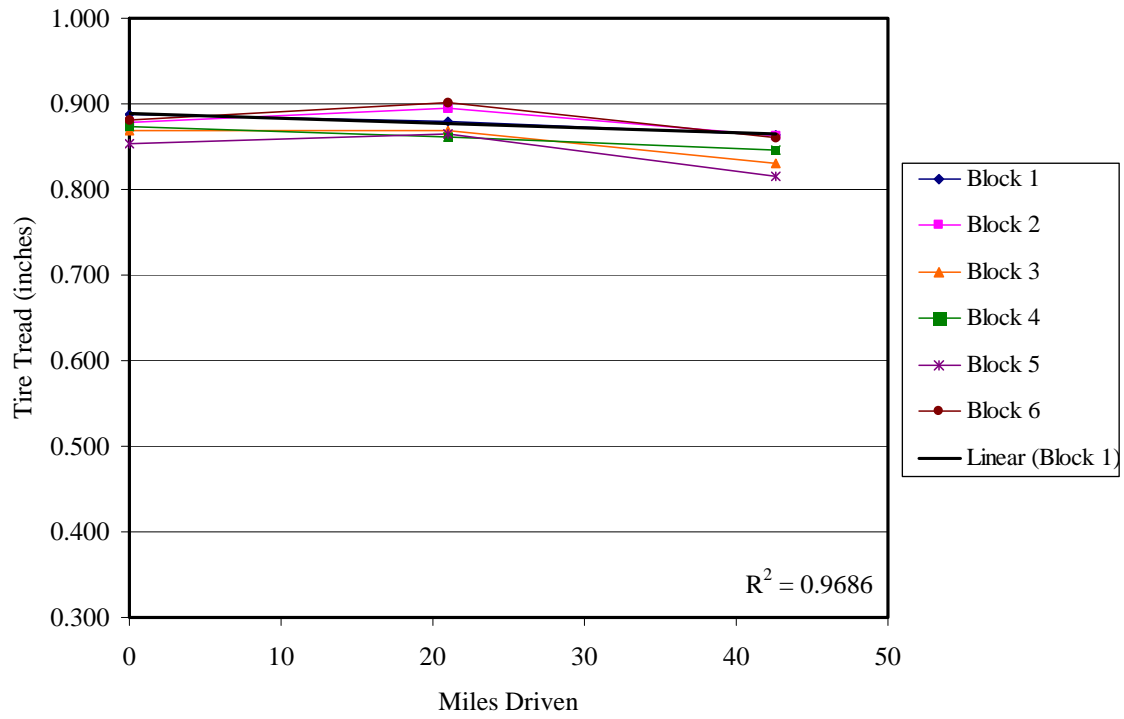


Figure 16. Right Middle Tire Tread Wear Data With RWS

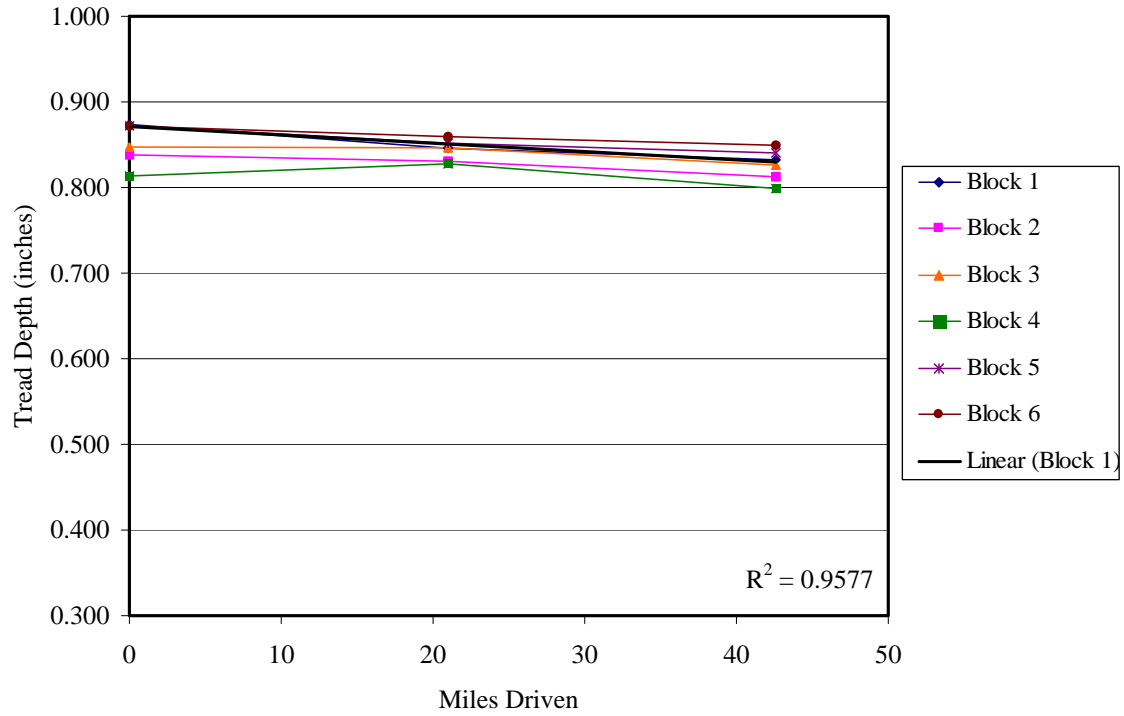


Figure 17. Left Middle Tire Tread Wear Data With RWS

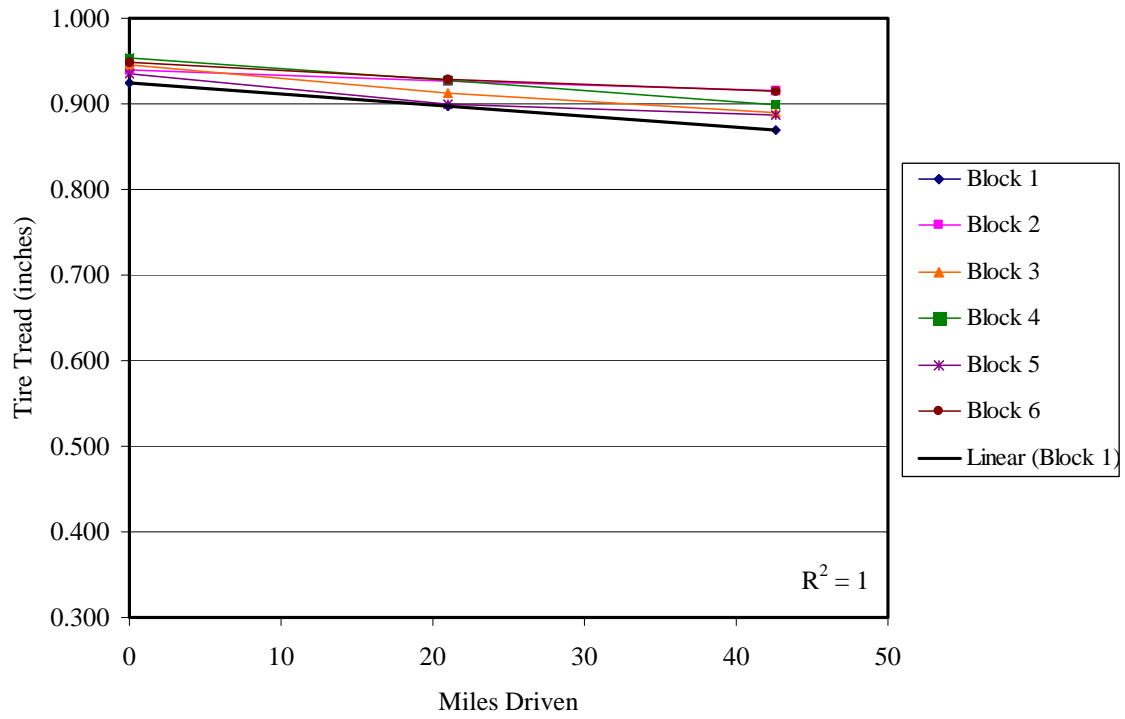


Figure 18. Right Rear Tire Tread Wear Data With RWS

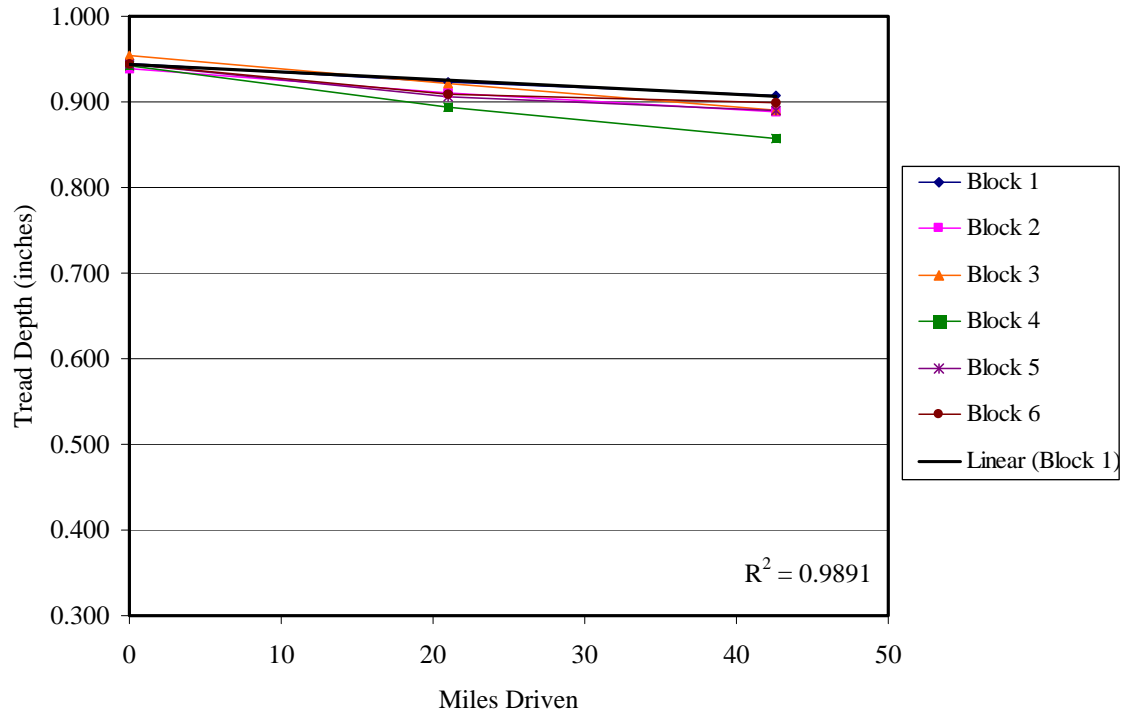


Figure 19. Left Rear Tire Tread Wear Data With RWS

### CALCULATED MAXIMUM TIRE LIFE.

The equation generated by the linear regression was used to determine the maximum tire life based on measurements taken for block 1. The maximum tire life was based on replacing the middle and rear axle tires at 0.0625 (2/32) inch of tread depth and replacing the front axle tires at 0.125 (4/32) inch tread depth in accordance with federal regulations. Figure 20 shows the differences in calculated maximum tire tread life based on axle location and use of RWS. For rear axle tires, RWS extended the life of the tires by 7 to 11 times compared to tire life without RWS. For front axle tire, RWS extended tire life by 1.6 to 2.4 times that of tire life without RWS.

For the middle axle tires, some irregularities in tire wear were observed. RWS did not extend tire life compared to testing completed without RWS and the right middle tire showed better tire life than the left, whereas the left front and rear tires showed better tread wear. This phenomenon was likely due to the geometry of the steering system and wheel alignment. Some tires are forced to slip sideways during a turn and, therefore, experience greater wear. This slip was increased with RWS, causing greater tire wear than without RWS.

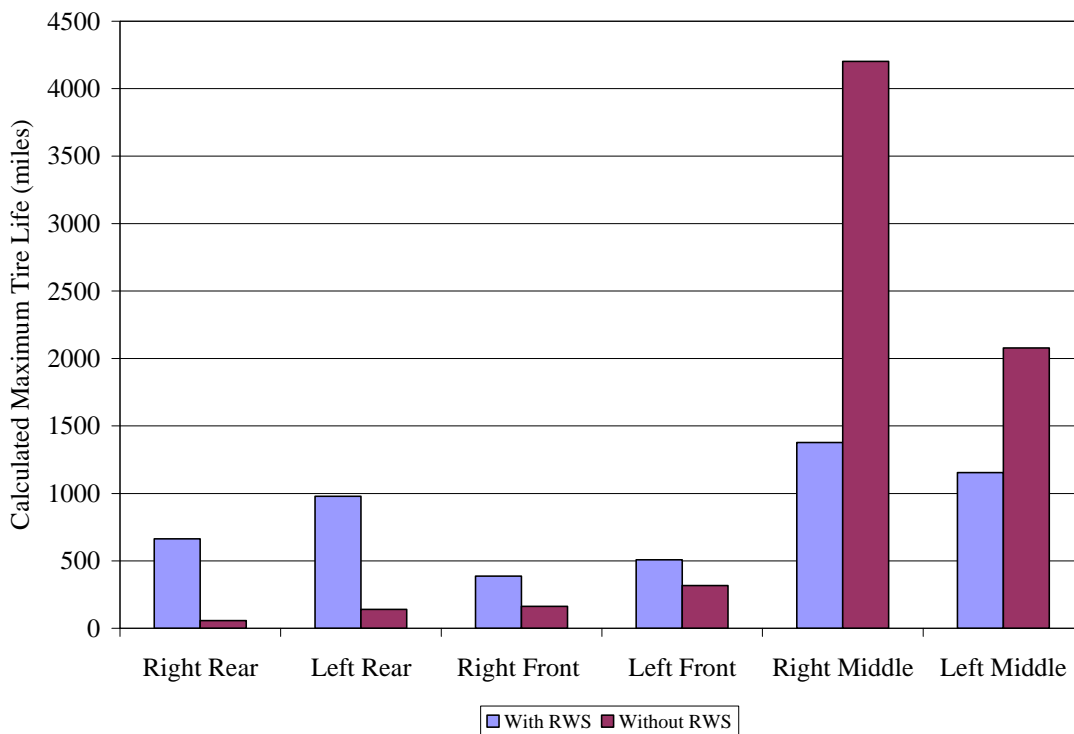


Figure 20. Calculated Maximum Tire Life Based on Linear Regression Equations

### CUSTOMER SURVEY.

Eleven airport fire departments responded to the request for information regarding ARFF vehicles and tire wear. Nine vehicles were 6x6 models and two were 8x8 models. Three of the eleven vehicles did not have RWS. Most airport fire departments reported having vehicles with

and without RWS in their fleets, which led to good comparative information. The information received from the airport fire departments showed a wide range of variation in the age and use of these vehicles. All respondents indicated that vehicles with RWS showed less tire wear, resulting in extended tire life. One responding airport fire department indicated that they were replacing the tires on a vehicle without RWS every 1000 miles, while another airport fire department reported getting 5500 miles between changes on a vehicle with RWS. Many other responding airport fire departments had less than 5000 miles on the vehicles and have yet to need replacements on those vehicles. Another common comment was the perceived increase in stability and handling of the vehicle with RWS by the various vehicle operators.

The airport fire departments also reported a significant difference in the amount of time needed to purchase replacement tires. The larger airports reported receiving replacement tires in as little as 1 week, while some of the smaller airports stated that procurement could take 4 to 9 months. Delivery of replacement tires averaged 4 to 6 weeks. The primary factors affecting the availability were location of the tire dealer as well as the priority given to the military for vehicles deployed overseas using the same tire.

## CONCLUSIONS

Results showed that rear-wheel steering (RWS) improved the turning diameter of the Federal Aviation Administration (FAA) aircraft rescue and firefighting (ARFF) vehicle in both the clockwise and counterclockwise directions. With RWS, the turning diameter decreased 8.8 feet (9%) in the clockwise direction and 11.32 feet (11%) in the counterclockwise direction.

Analysis of the video recorded during testing did not show any significant differences in tire deflection with or without RWS. The Air Force Research Laboratory (AFRL) and the FAA could not make any direct correlations between the amount of sidewall deflection with or without RWS and the overall side forces incurred by the vehicle while in an aggressive turn. The AFRL and the FAA concluded that the video test method could not accurately depict the side load forces on the vehicle.

The front and rear tires on both sides showed significantly less tread wear over an equivalent 40-mile distance versus the wear measured without RWS. For the rear axle tires, RWS extended the life of the tires by 7 to 11 times compared to tire life without RWS. For the front axle tires, RWS extended tire life by 1.6 to 2.4 times that of tire life without RWS.

All airport fire departments that responded to the customer survey indicated that the ARFF vehicles equipped with RWS showed less tire wear, resulting in extended tire life, and increased stability/handling of the vehicle. Delivery of replacement tires averaged 4 to 6 weeks and ranged in price from \$2500-\$3500 per tire plus installation fees.